SYNCHRONIZED WIDE REGIONAL ACTIVATION OF SEISMIC ACTIVITIES AND MATHEMATICAL MODELING

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ABSTRACT

Pattern dynamics of small earthquake activities in and around Japan are presented. Global seismic activities are classified into (1) random, (2) localized, (3) quiescent, (4) synchronized wide regional activation (several hours), and (5) traveling wave (10-80km/hour) patterns. All these phenomena imply that earth's crust is quite abundant of various stress/strain waves. Apparently, very long periods, long wave length and slow moving waves seem to exist in the crust that have never been identified before. Obviously they are not derived from the regime of elasticity. A simple mathematical model which consists of coupled oscillators contact with the inelastic ductile layer is introduced. Simulations show existence of various stress/strain waves that may account for various patterns of seismicities.

1. Introduction

For last several decades, the earthquake phenomena have been talked by the theory of elasticity. However, recent seismological observations have shown that actual situation is not the case. Contrary, the physical state of the crust is far from the regime described by the theory of elasticity. Particularly, actual stress/strain field in the crust and the problem of earthquake generation are not well understood yet, which is, indeed, the most important subject in geophysics.

In this study, we present pattern dynamics of earthquake activities in and around Japan and show that the earth's crust is more dynamical than has been considered before. Also, we present various aspects that can not be expected from the regime of elasticity.

First, we through a light on the global behaviors of small earthquakes called microearthquakes. Then, we attempt to construct a simple mathematical model, a kind of coupled oscillators, to describe the crustal dynamics. In this paper, we present mainly results obtained from the analysis of the earthquakes catalogue of the Japan Meteorological Agency (JMA), since earlier results obtained by ocean bottom seismometers (OBSs) were already reported in detail in the preceding paper (Ouchi et al.,1993).

2. Microearthquakes and the Background Seismicity

The occurrence of earthquakes is a phenomenon of sudden creation of fractures in the crust. They release energy and transmit seismic waves. Size of earthquakes are measured in terms of well known concept of magnitude M, which is related to the released seismic wave energy E as

$$\log E = 11.8 + 1.5\,M.$$

Here in this study, we call very small earthquakes, smaller than magnitude about 4 "microearthquakes". We focus our interests on behaviors of such small microearthquakes. Global behaviors of microearthquakes will give us quite valuable information about the stress/strain state of the crust, although exact process of the microearthquake generation is not well understood. Basic idea of this study is that we can use these microearthquakes as detectors or sensors to investigate the space-time variation of the stress/strain state in the crust, since they are considered to be very sensitive to the local stress/strain field. Simply speaking, if the stress or strain state at some place exceed a certain level, then microearthquakes will occur. This process is certainly quite stochastic. However, we may know, to certain extent, the variation of stress/strain state in the crust.

In general, ordinary seismicities or earthquake activities can be classified into following three major patterns. First is the well known sequences of large earthquakes with foreshocks and aftershocks (type 1). Earthquakes tend to take place more or less in cluster. We call a earthquake cluster without dominant events "earthquake swarm". Usually such a swarm is localized in a quite limited area of several km (type 2). Small microearthquakes are occurring almost ceaselessly in the whole area of Japan. Such activities may be regarded as "background seismicities" (type 3).

Here, a serious question arises about such ordinary background seismicities. "Are these microearthquakes occurring quite randomly ?"

This is the starting point of this research. In reality, non-randomness of microearthquake occurrences has been suggested by many seismologists not only in the inland regions but also in the oceanic regions (e.g., Walker, 1988; Ooida, 1989). Sometimes microearthquakes in different regions show significant correlations in their occurrences. Such phenomena have different scales both in time and space. We also have noticed nonrandom or synchronized occurrences of microearthquakes in unusually wide regions by the OBS observation (Ouchi et al., 1993).

3.Synchronized Wide Regional Activation of Seismicities

Synchronized wide regional occurrences of earthquakes were firstly recognized by the OBS study. OBSs have enabled us to detect such unusual wide regional earthquake activities since high frequency waves of 5-20 Hz propagate quite efficiently in the oceanic regions. Surprisingly, we can detect small microearthquakes of magnitude 3 at distant stations over a thousand km (Ouchi et al., 1993).

Here, we show some intriguing seismic activities revealed by OBSs. First is the one found in the observation conducted at the Marcus region in the northwestern Pacific from June to July in 1981 (Ouchi et al.,1993). During about one month observation, a number of microearthquakes that occurred along Japan were recorded by OBSs in the Marcus region. Many tiny events occurred on July 9 and at a glance the activity appeared to be a small scale swarm. However, this activity was quite unusual. They took place almost simultaneously in about 5 hours but interestingly they spread almost as wide as more than 5 hundred km (Fig.1). It should be stressed here that ordinary swarms have sizes of at most several tens km. Second case is also a small earthquake cluster (Fig.2). Again these events have quite different origins, probably they were several hundred km separated from one another. Apparently earthquakes appeared to migrate over several hundreds km and approach against the OBSs at the Marcus area.

4.Analysis of Earthquake Catalogue

Next, we have analyzed the earthquake catalogue of JMA from 1960 to July, 1991 to substantiate the results obtained by the OBS study.

Numerous earthquakes are occurring almost ceaselessly in the whole area of Japan and its vicinity but most of events are very small microearthquakes. We projected their epicenters onto two NE-SW and E-W lines to investigate the space-time distribution of them. This procedure may seem to be too crude. In actual situations, however, it is not so implausible to see the space-time variation of seismicities one dimensionally, since most earthquakes are taking place in a very shallow part of the crust within about 50 km and in a rather narrow limited zone of a couple of hundreds km along Japan.

Most patterns of space-time distributions of earthquakes are random but we found many unusual patterns as well as synchronized wide regional activities similar to those found in the OBS study.

(a) Synchronized Wide Regional Activation of Seismic Activities

Fig.3a shows the earthquake distribution of about two weeks from April to May in 1973. Fig.3b is the space-time distribution of these events. They are projected on the dashed line in Fig.3a. This is the phenomenon of "synchronized wide regional activation of seismicities" similar to those obtained in the OBS observation. In about two weeks, a total of 13 events were registered but 7 consequently most events occurred on May 5 in only about 8 hours. This activity covered almost whole area of Japan. Before and after this episode the seismicity was rather quiet. Fig.4a shows the other case on December 23, 1984. Fig.4b is the space-time distribution of earthquakes. Synchronized earthquakes, most events occurred in the western part of Japan, are projected on the W-E line. In this case, a small deep event of 351 km took place at first, then about one hour later 6 events occurred simultaneously during about 30 minutes.

It should be mentioned here that frequencies of earthquakes of these cases are different but this is due to the different detection capability of earthquakes of JMA. In other words, detection capability was not uniform and increased year by year but this will not affect the results seriously as long as we investigate the variation of seismicities in short periods of from several weeks to several months.

We have found numbers of such phenomena of synchronized global activations of earthquakes. In addition, one interesting feature was noted that such synchronized activities tend to occur successively, one day or longer separated. Also, reduced activities of earthquakes seem to appear in many cases prior to such phenomena.

(b) Traveling Wave Patterns

The next case is more interesting (Figs. 5a and 5b). Earthquake activities sometimes show remarkable trend or seem to migrate toward north-east or south-west directions. Estimated velocity of these traveling waves vary from 10 to 80 km/hour. Occasionally, synchronized and traveling wave patterns appear together.

(c) Localized and Quiescent Patterns

From time to time drastic changes appear in the global seismicities. Fig.6a shows 5 days variation of the seismicity from May 22, 1991. Before May 24, almost no earthquakes occurred in the western part of Japan and the earthquake activity has started suddenly on that day. Fig.6b shows a concentrated pattern around the central part of Japan that lasted a couple of days. Conversely, quiet periods appeared in both north-east and south-west parts of Japan. Before and after this period, the earthquake activity distributed almost whole area of Japan.

5.Patterns of Seismic Activities

Patterns of major background seismicities in and around Japan are summarized phenomenologically as;
(1) random, (2) localized, (3) quiescent, (4) synchronized wide regional activations (in several tens minutes - several hours) and (5) traveling waves (10-80 km/hour).

All these phenomena indicate that the crust is quite abundant of various stress/strain waves, since microearthquakes readily reflect the variation of stress/strain state of the crust. Apparently, very long periods, long wave length and slow moving stress/strain waves seem to exist in the crust. They have time scales of several hours - several days, their wave lengths are several hundreds km and their velocities are in a range of several tens km/hour but differ from case to case. Thus, they are not ordinary seismic waves.

These phenomena have never been identified and absolutely missed before. In what follows, the earth's crust is more dynamical than we have expected. Apparently the global pattern of the stress/strain field is always changing from time to time and from place to place. This can not be understood by the theory of elasticity but we must introduce some idea of the inelastic regime.

6.Modeling of the Crustal Dynamics

Recent seismological observations have revealed that the crust, in general, has a considerably complicated structure. Conventionally, the crust has been regarded as a continuum elastic medium. However, it has turned out now that the crust is highly fragmented or segmented and have block structures. Roughly speaking, such block dimensions are considered to be from 5 to 50 km (e.g., Tsuboi, 1933; Bilham and Beavan, 1979). Also, we must consider some inelastic regime for the crustal dynamics. Particularly, we must take account of visco-elastic effects as well as plastic properties. In addition, we must introduce a brittle-ductile layered structure, which is now widely accepted picture of the crust (e.g., Hasegawa, et al., 1991).

Conventionally, the dynamics of the crust has been discussed based on the wave equations, derived from the theory of elasticity. Alternatively, we present a simple model to describe the crustal dynamics according to the recent picture of the crustal structure mentioned above. This model is simple discrete one dimensional and consists of a chain of blocks and springs. This chain of blocks contacts with a beneath semi-ductile layer (Fig.7). Kinetic motion of this system is represented as

$$m \frac{d^2U_n}{dt^2} = k(U_{n+1} - 2U_n + U_{n-1}) - F(U_n, \dot{U}_n, \cdots) + R(t).$$

Here U_n denotes displacement at n-th segment and $F(U_n, \dot{U}_n, \cdots)$ represents the drag force from the semi-ductile layer and the reaction force from individual block. This U_n should be understood to be deviation from the equilibrium state. The external force $R(t)$ that includes various effects such as the fluctuation of the plate motion, tide and so on. In this study, a quite simple situation is assumed as

$F(U_n, \dot{U}_n, \cdots) = \alpha + \beta U_n + \gamma \dot{U}_n,$

for the sake of simplicity although this term should be basically non-linear. α and β are constants. Also a simple random Gaussian noise is considered here at the one end as the external force $R(t)$.

Numerical simulations show that various strain waves exist in this system although this is quite a simple one. Under general conditions, very long periods, long wave length and slow moving strain waves exist, which are expected from the patterns of global seismicities in and around Japan (Fig.8). Apparently they are not ordinary seismic waves. Further, traveling waves but with different velocities and wave lengths appear quite generally. They may be interpreted to be dispersion phenomena of different wave modes due to the block structures and viscous force introduced in the system (Sato, 1977). Microearthquakes may be expected to occur at highly strained regions whereas it will become quiet in low strained regions.

8.Discussions and Summary

Analysis of the global behaviors of microearthquakes in and around Japan showed that their occurrences are not random. Conversely, various patterns of seismic activities such as synchronized and traveling patterns indicate that earth's crust is abundant of stress/strain waves of different modes.

The scales of these phenomena are from several minutes to several hours or may be longer in time and several hundred km in space. Previously, migration of large earthquakes and propagation of crustal movement have been reported (e.g., Kasahara, 1979). However, the estimated velocities of crustal movement were in a range of several tens km/year and time scales are from several tens years. Synchronized wide regional activation of seismicities of several months were also noted (e.g.,Ooidá,1989). Consequently, they may be different, at least phenomenologically, from new findings shown in this study. Physically, the former will be understood as phenomena of diffusion and may be modeled in terms of the diffusion scheme where inertial effects are ignored (Ouchi, 1985). The latter will be regarded as inelastic waves and may be represented by nonlinear models such as coupled oscillators.

The modeling presented in this study is just seminal one dimensional and explanatory. However, various patterns of microearthquakes like synchronized and traveling wave patterns might be, to some extent, explained by such a strain field. Certainly, future study is necessary to substantiate above results and we now plan to introduce non-linear effects to the model.

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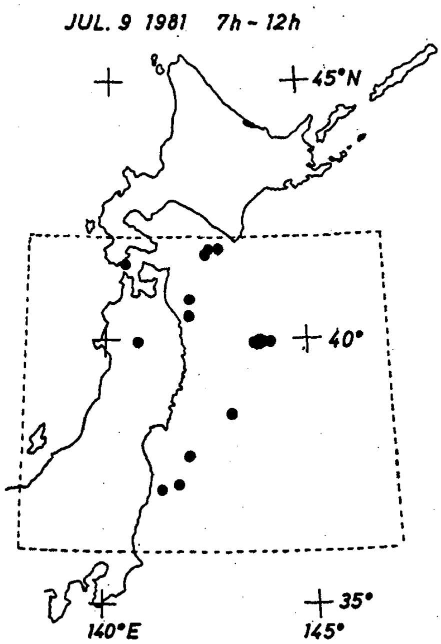

Fig.1 Epicenter distribution of swarm earthquakes (solid circles in the dashed line) form 7:00 to 12:00 on July 9, 1981. They were determined by the microearthquake observation network of Tohoku University. Note unusually wide distribution of earthquakes.

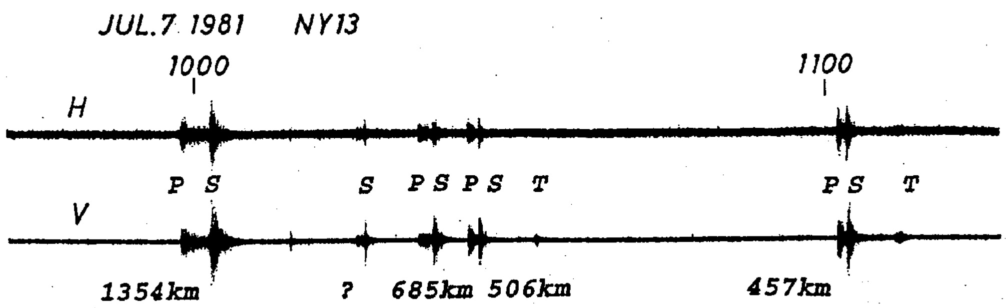

Fig.2 Earthquakes observed by the OBS NY13 (29° 9.64', 149° 3.05') placed near Marcus island in the northwestern Pacific. Microearthquakes transmit seismic body waves with about from 1 to 20 Hz. P, S and T show dilatational, shear, and water waves, respectively. H and V show horizontal and vertical components of seismometers. Bottom numbers are distances between the hypocenters of earthquakes and the OBS station estimated from arrival times P and S waves. Distance of the second event was not obtained because the onset of P wave was emergent.

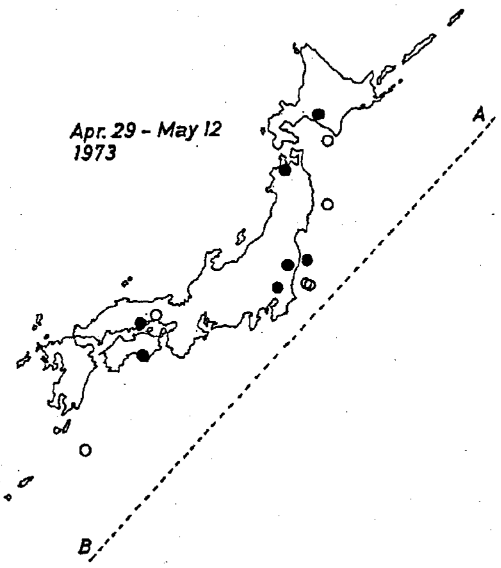

Fig.3a Distribution of earthquakes from April 29 to May 12 in 1973. Solid circles show the events of the "synchronized wide regional activation phenomenon" and open circles are ordinary background earthquakes.

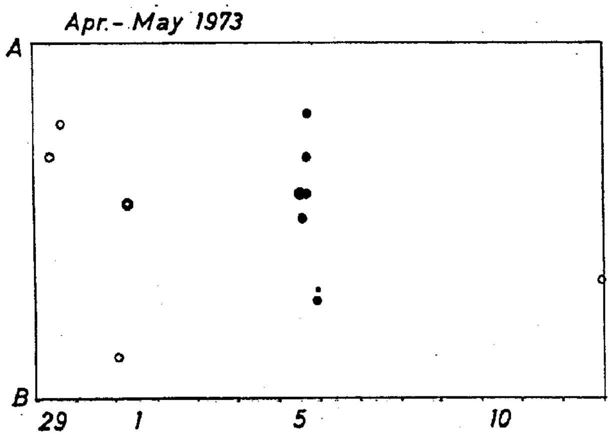

Fig.3b Space-time plot of earthquakes shown in Fig.3a. Earthquakes are projected onto the dashed (NE-SW) line in Fig.3a.

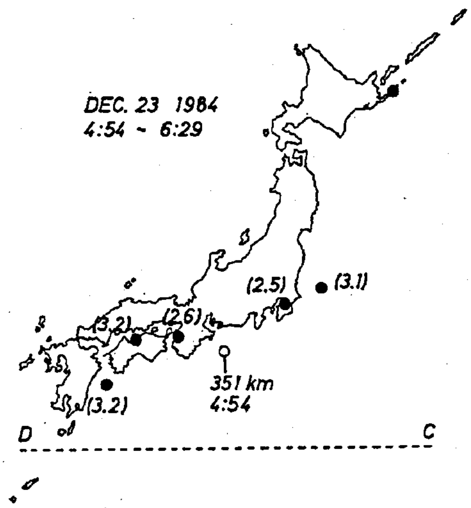

Fig.4a Distribution of earthquakes (solid circles) of the "synchronized wide regional activation phenomenon". The arrow denotes the deep event. Numbers in the parenthesis are magnitudes.

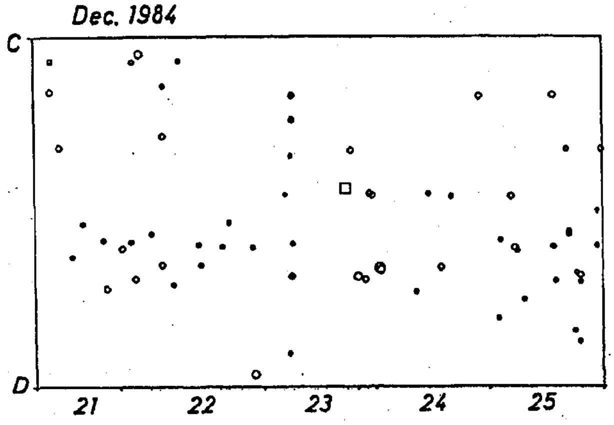

Fig.4b Space-time plot of earthquakes. Earthquakes are projected onto the dashed (W-E) line in Fig.5a. It should be noted again their wide distribution. Squares represent deep events (> 140 km).

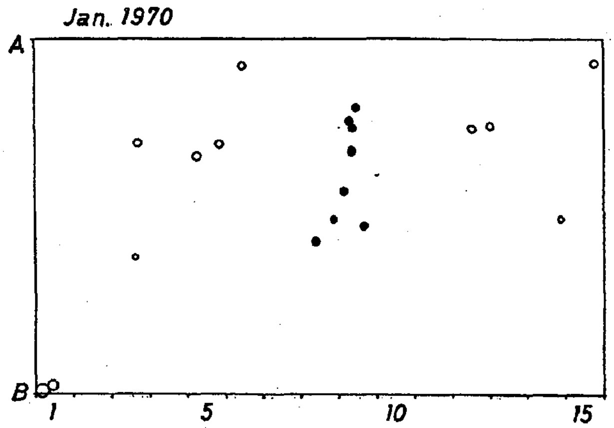

Fig.5a Space-time distribution of earthquakes. Earthquakes are projected onto the NE-SW line. Solid circles show the "migration of earthquakes".

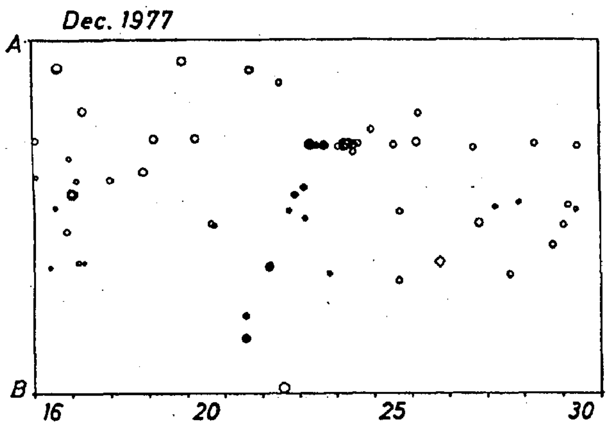

Fig.5b Space-time distribution of earthquakes. Earthquakes are projected onto the NE-SW line. Solid circles show the "migration of earthquakes".

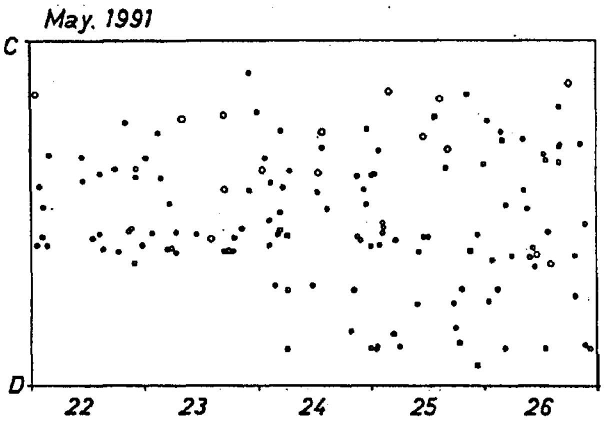

Fig.6a Space-time distribution of earthquakes. Earthquakes are projected onto the NE-SW line.

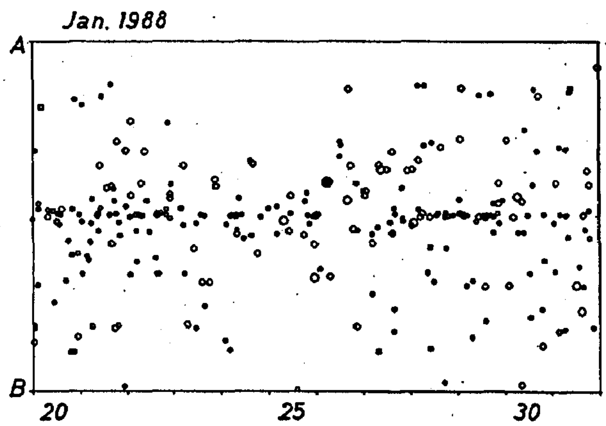

Fig.6b Space-time distribution of earthquakes. Earthquakes are projected onto the NE-SW line.

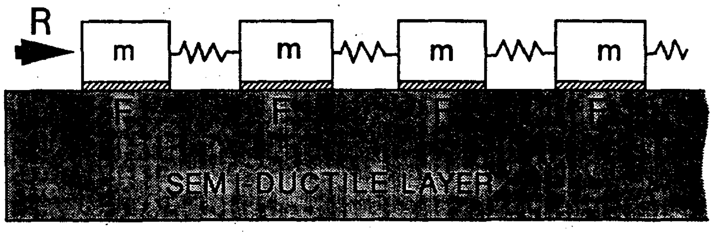

Fig.7 The one dimensional system of blocks connected by springs which contacts with the beneath semi-ductile layer. The arrow shows the external force added at the one end or the plate boundary. See details in the text.

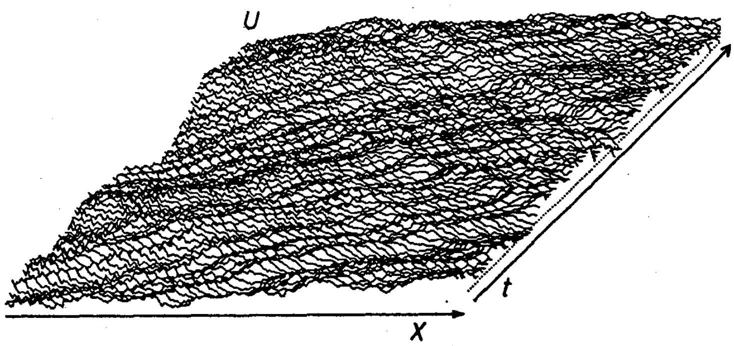

Fig.8 Time evolution of displacement pattern. Random external force is added at the one end as a drive force of this system. In this case, $\partial U/\partial x = 0$ is assumed at both ends as the boundary condition.